Final Report

From Clicks to Counts: Using Passive Acoustic Monitoring to Estimate the Density and Abundance of Cuvier’s Beaked Whales in the Gulf of Alaska (GoA)

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Cuvier’s beaked whale (*Ziphius cavirostris*). Photo taken by Todd Pusser, available on naturepl.com (image #01138327).
Executive Summary

The Gulf of Alaska (GoA) is home to three known species of beaked whales, Baird’s (*Berardius bairdii*), Cuvier’s (*Ziphius cavirostris*), and Stejneger’s (*Mesoplodon stejnegeri*). Beaked whale distribution and abundance is poorly understood with only limited sightings within the GoA (Allen and Angliss 2013). To address gaps in knowledge regarding the distribution and abundance of beaked whales and other marine mammals in the GoA, a 26-day visual and acoustic line-transect survey was conducted during the summer of 2013. One of the main objectives of the acoustic survey was to obtain acoustic-based density and abundance estimates for Cuvier’s beaked whales in the study area. The survey area was divided into four strata to reflect distinct marine mammal habitat types; ‘inshore’, ‘slope’, ‘offshore’ and ‘seamounts.’ Passive acoustic monitoring was conducted around the clock for 23 days over 6,304 kilometers (km) of trackline using a towed hydrophone array system. There were 93 acoustic encounters of beaked whales (32 Baird’s, 47 Cuvier’s and 14 Stejneger’s), of which 79 (85 percent) were localized during post-processing. Of these localized encounters, 18 Baird’s, 40 Cuvier’s and 10 Stejneger’s occurred during line-transect effort. Cuvier’s beaked whales were the only species of beaked whale with a sufficient sample size to reliably estimate density and abundance using line-transect distance sampling methods. Comparatively, visual survey methods resulted in only one sighting of Cuvier’s beaked whale (one individual), six sightings of Baird’s beaked whale (49 individuals) and five unidentified beaked whale encounters (nine individuals) during 4,155 km of visual effort. Line-transect distance sampling methods were used to estimate the density and abundance of Cuvier’s beaked whales using the acoustic data. Encounter rate varied by strata, and was highest in the seamount stratum (10 animals/1,000 km), followed by the offshore (7 animals/1,000 km) and slope strata (3 animals/1,000 km), respectively. An acoustic-based density and abundance estimate was obtained for each stratum Offshore: $\hat{N}/1,000$ km$^2 = 0.20$; $\hat{N} = 122$; CV$_b = 48$ percent; Seamount: $\hat{N}/1,000$ km$^2 = 0.30$; $\hat{N} = 138$; CV$_b = 30$ percent; and Slope: $\hat{N}/1,000$ km$^2 = 0.08$; $\hat{N} = 31$; CV$_b = 74$ percent) and for the entire survey area (A $= 142,204$ km$^2$; $\hat{N}/1000$ km$^2 = 0.21$; $\hat{N} = 291$; CV$_b = 28$ percent) Results from this study represent the first estimates of density and abundance for Cuvier’s beaked whales within the GoA, and the first acoustic-based estimates for any species of beaked whales using a line-transect survey design.
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Acronyms and Abbreviations

µs micro-second(s)
BOEM Bureau of Ocean Energy Management
CV_b coefficient of variation (bootstrapped value)
CI_b 5% to 95% Confidence Interval (bootstrapped values)
dB decibel(s)
g(0) the probability of detecting an animal on the trackline
GoA Gulf of Alaska
GOALS II Gulf of Alaska Line-Transect Survey II
kHz kilohertz
km kilometer(s)
km² square kilometer(s)
m meter(s)
ms millisecond(s)
PAM passive acoustic monitoring
TDR time-depth recorder
TMAA Temporary Maritime Activities Area
U.S. United States
1. Introduction

The Gulf of Alaska (GoA) is home to three known species of beaked whales, Baird’s (*Berardius bairdii*), Cuvier’s (*Ziphius cavirostris*), and Stejneger’s (*Mesoplodon stejnegeri*). Due to their cryptic behavior and small size, beaked whales are poorly understood cetaceans with only limited sightings occurring within the GoA (Rone et al. 2014; Allen and Angliss 2013). However, beaked whales produce distinctive echolocation clicks that can be acoustically detected and differentiated from one another and from other odontocetes based upon distinctive acoustic features, such as peak frequency (Baird’s = 16–22 kilohertz [kHz], Cuvier’s = 38–40 kHz, and Stejneger’s = 45–66 kHz), inter-click interval (Baird’s = 204 milliseconds [ms], Cuvier’s = 337 ms, and Stejneger’s = 90 ms) and the presence of frequency upsweeps in their clicks (Baumann-Pickering et al. 2013).

Beaked whales spend a majority of their time submerged, regularly dive to depths of hundreds to thousands of meters, often occur in small groups, and behave inconspicuously at the surface (Tyack et al. 2006, Arranz et al. 2011). These factors make them difficult to detect and study using visual survey methods alone. However, Cuvier’s beaked whales are known to produce distinctive echolocation clicks almost continuously below depths of approximately 200 meters (m) during deep foraging dives (Tyack et al. 2006). This stereotypical behavior combined with recent advancements in passive acoustic detection and survey techniques have made passive acoustic monitoring (PAM) a viable method for studying the occurrence and distribution of these elusive animals (Yack et al. 2013). Cuvier’s beaked whales are a relatively large, deep diving species of cetacean with a cosmopolitan distribution in deep temperate and tropical waters. Presently, there is no known population estimate for Cuvier’s beaked whales in the GoA and this species is considered ‘Data Deficient’ by the International Union for Conservation of Nature Red List (Taylor et al. 2008).

Reliable information about the distribution and abundance of populations of marine mammals in the GoA is necessary for effective conservation and management of these living marine resources. The United States (U.S.) Navy periodically uses a Temporary Maritime Activities Area (TMAA; 144,560 square kilometers [km²]) in the central GoA, east of Kodiak Island (*Figure 1*). The TMAA encompasses a diverse habitat consisting of the continental shelf, slope, and offshore pelagic waters with numerous seamounts in the offshore region (*Figure 1*). In order for the Navy to conduct training exercises, analyses on the potential impacts of naval operations on biological and environmental resources are required. In 2009, the U.S. Navy funded a line-transect survey that provided density and abundance estimates for fin and humpback whales, as well as limited distribution information for several other species (Rone et al. 2010). That survey was successful in gathering important data on the marine mammal species present in this largely unexplored area. However, additional data on regionalized species’ densities were needed for the Navy and other participating Federal agencies like the Bureau of Ocean Energy Management (BOEM) to meet their environmental stewardship obligations (Rone et al. 2014). To accomplish this, the Navy sponsored a line-transect survey of marine mammals in the summer of 2013.

To better assess the occurrence and distribution of visually elusive marine mammals, such as beaked whales, PAM using a towed hydrophone array was implemented to complement
traditional visual survey methods. The main objective of this study was to use passive acoustic data collected during a line-transect survey to estimate Cuvier’s beaked whale density and abundance. Density and abundance values were estimated both globally, and by strata, for the survey area.

Line-transect survey and analytical methods are well developed for estimating abundance of marine mammals using visual sighting data (Buckland et al. 2001, Holt 1987, Kinzey et al. 2000). Distance sampling accounts for undetected animals by considering that animals are less likely to be detected at increasing range from the trackline. A statistical model known as the ‘detection function’ is fit to all the observed perpendicular detection ranges and is then used to estimate the average probability of detecting an animal (Buckland et al. 2001). These methods require that the following two important assumptions are met: 1) accurate measurements of the perpendicular (i.e. horizontal) distances of animals from the survey trackline are made, and; 2) either all animals on the trackline will be detected \([g(0) = 1]\), OR the trackline detection probability is known.

Recently, as a result of an increased and focused effort to use passive acoustic data from vocalizing animals for density estimation, a comprehensive suite of methods (including distance sampling) was demonstrated across a range of different survey designs, instrument configurations, survey platforms, and study species (as reviewed in Marques et al. 2013). Line-transect distance sampling methods have been effectively applied to passive acoustic data collected from marine mammals using a hydrophone array towed behind the survey vessel (Leaper et al. 1992, 2000; Barlow and Taylor 2005; Swift et al. 2009). However, to apply these methods effectively for Cuvier’s beaked whales, two issues related to the above assumptions must be addressed. The first is that using a linear towed array to estimate animal location provides a slant range rather than the perpendicular distance required for distance sampling. Slant ranges can only be interpreted as perpendicular ranges if it is assumed that vocalising animals are on the same horizontal plane (i.e. depth) as the hydrophone array. If this assumption is violated, the slant ranges used for a distance sampling analysis will be an overestimate of the true perpendicular distances. This will result in overestimation of the average probability of detection, consequently, resulting in an underestimation of density.

Second, the probability of detecting a beaked whale at a zero perpendicular distance from the trackline, commonly referred to as \(g(0)\), cannot be assumed equal to one. This parameter depends on the temporal patterns of the animals’ vocalizations (i.e., an animal will not be detected if it is not vocalizing). Fortunately, three recent studies have examined these issues in detail and provide solutions to estimate abundance and density for Cuvier’s beaked whales (Barlow et al. 2013, Harris et al. 2014, Yack et al. 2015).

Yack et al. (2015) built on work conducted by Harris et al. (2014) to evaluate the effect of using slant ranges to estimate density and abundance. In this study, conventional distance sampling methods were compared to an alternate distance sampling method that incorporated a depth distribution model into the detection function estimation algorithm (Harris et al. 2014). This approach was used to quantify the underestimation bias resulting from using slant ranges with conventional distance sampling methods. This work demonstrated that conventional distance sampling using slant ranges resulted in an underestimation of density and abundance when
compared to the analysis that incorporated a depth distribution model into the detection function estimation algorithm. The underestimation bias calculated for using conventional methods with slant ranges was approximately 20 percent. However, in the absence of methods to effectively model the animals’ depth distribution, the issue can be treated as a measurement error and the data can be binned prior to analysis (Buckland et al. 2001). The application of the binning method to the Cuvier’s beaked whale slant range data (when compared to the depth distribution model) showed that this method reduced the underestimation bias by 16 percent (Yack et al. 2015).

To address the issue of $g(0) \neq 1$ for Cuvier’s beaked whales, Barlow et al. (2013) developed methods to estimate $g(0)$ based on the assumption that a beaked whale will be detected if it is producing regular echolocation clicks. Data from acoustic recording tags were used to directly estimate the percentage of time Cuvier’s beaked whales produce echolocation clicks (i.e., are actively foraging). A model of vocal behavior for these species as a function of their diving behavior was applied to other types of dive data (from time-depth recorders [TDRs] and time-depth-transmitting satellite tags) to indirectly determine $g(0)$ in other locations for low ambient noise conditions. The methods developed and results provided by Barlow et al. (2013) can be used to estimate $g(0)$ for other surveys. Herein, we apply the methods developed and described above and the knowledge gained from recent studies (Barlow et al. 2013; Harris et al. 2014; Yack et al. 2015) to estimate the abundance and density of Cuvier’s beaked whales in the GoA study area.
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2. Methods

2.1 Survey

The Gulf of Alaska Line-Transect Survey II (GOALS II) was conducted from 23 June to 18 July 2013 aboard a 50-m commercial fishing vessel, the R/V Aquila. This vessel was custom outfitted for research operations including the use of towed hydrophone arrays, small-vessel deployment and retrieval, and marine mammal observer operations. Marine mammal observations were conducted whenever weather and sea conditions allowed during daylight hours. Passive acoustic operations were conducted around the clock. Four survey strata based on four distinct habitats within the study area were designated prior to the survey to optimize survey effort. The four strata were: 1) the continental shelf or ‘inshore’ stratum, 2) the ‘slope’ stratum, 3) the pelagic or ‘offshore’ stratum, and 4) the ‘seamount’ stratum. The line-transect survey was designed to provide uniform coverage within each stratum, and was based upon the equal-spaced ‘zigzag sampler’ (Strindberg et al. 2004) (Table 1, Figure 1).

Table 1. Strata and proposed effort allocation for the GOALS II research cruise.

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Area (km$^2$)</th>
<th>No. of Tracklines</th>
<th>Proposed Effort</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>km</td>
</tr>
<tr>
<td>Inshore</td>
<td>22,749</td>
<td>18</td>
<td>1,296</td>
</tr>
<tr>
<td>Offshore</td>
<td>60,051</td>
<td>11</td>
<td>1,752</td>
</tr>
<tr>
<td>Seamount</td>
<td>45,377</td>
<td>25</td>
<td>2,610</td>
</tr>
<tr>
<td>Slope</td>
<td>36,776</td>
<td>18</td>
<td>1,986</td>
</tr>
<tr>
<td>Total</td>
<td>164,953</td>
<td>72</td>
<td>7,644</td>
</tr>
</tbody>
</table>
**Figure 1. Survey strata and tracklines for the GOALS II research cruise.** The red box indicates critical right whale habitat.
2.2 Acoustic Monitoring

PAM consisted of a towed hydrophone array system. The hydrophone array was towed 300 m behind the *Aquila* and was connected to an acoustic monitoring and processing center onboard the ship’s lab on deck. The towed hydrophone array consisted of five hydrophone elements (i.e., channels) with custom designed preamplifiers. The hydrophones consisted of two high frequency Reson TC 4013 hydrophones (flat frequency response [±/− 1.5 decibels (dB)] from 1 to 180 kilohertz [kHz]; 35-dB gain) and three mid-frequency hydrophones (APC International, Inc. 42-1021; flat frequency response [±/− 1.5 dB] from 1 to 100 kHz; 36 dB gain). Analog acoustic signals from the array were passed up the 300-m tow cable to the deck of the research vessel and then through a signal conditioning filter/amplifier (Ecologic HP/27ST Magrec Stereo Monitor Box) that was part of the acoustic monitoring and processing center. The Magrec HP/27ST was used for high-pass filtering and adjusting the gain for each channel. Using the Magrec HP/27ST, the hydrophone signals were high-pass filtered at 1 kHz. All channels were then passed to two separate RME (model FireFace UFX/UCX) data acquisition boards and digitized at a sample rate of 192 kHz or 484 kHz (Inshore stratum only). Signals from each RME were passed to ‘manual’ and ‘semi-automated’ processing systems for tracking and localization.

Signal processing, localization, recording, and documentation were achieved through a combination of programs including *Ishmael* (Mellinger 2001), *WhalTrak II* (created by Glen Gailey at Texas A&M University) (manual system), and *PAMGuard* (Gillespie et al. 2008; [www.pamguard.org](http://www.pamguard.org)) (semi-automated system). *Ishmael* was used to record acoustic data and obtain bearings to user selected vocalizations for localization via target motion analysis (Mellinger 2001). Two-channel recordings were made in .wav formats sampled at 192 kHz. Recordings were made continuously with files saved at 10-minute intervals. All acoustic data were backed up periodically (at least once per 24-hour period) to internal and external hard drives. *WhalTrak II* was used for manually localizing and plotting whistling cetaceans and compact groups. It also recorded the ship’s position, heading, and speed; estimated position of the array; and form data, using an MS Access database. *PAMGuard* was used as an automated click and whistle detector. It was configured using an automatic click classification module for sperm whales (*Physeter macrocephalus*), killer whales (*Orcinus orca*), Cuvier’s beaked whales, Baird’s beaked whales, Stejneger’s beaked whales, and porpoise (phocoenid spp.).

*PAMGuard* software was used to detect, classify and localize echolocation clicks from beaked whales in real-time. Echolocation clicks were localized using a semi-automated algorithm based on target motion analysis methods. *PAMGuard* was configured with an automatic click classification module that uses an energy band comparison to classify echolocation clicks to species for beaked whales. Click classification was conducted in real time to track echolocation click trains which were used to estimate slant ranges of individuals to the trackline. These echolocation click trains were assigned to individual animals, and bearings were plotted to *PAMGuard*’s mapping display to estimate the slant range distances.
2.3 Post-Processing

All beaked whale acoustic encounters, as well as off effort periods, were post-processed using PAMGuard ViewerMode software. Using the bearing/time display (Figure 2), click trains were assigned to individual animals in order to create tracks or 'events' for each encounter period. These data were processed in order to estimate slant range distances from the trackline to each animal/event. Target motion analysis was used to estimate bearings to individual clicks and either a least-squares or 2D simplex optimization algorithm was used to estimate the slant range distance from the trackline to the animal/event (Figure 3). In this analysis, the average of the left and right slant range distances from the best fit model selected by PAMGuard was used for distance sampling analysis.
Figure 2. Example of an acoustic Cuvier’s beaked whale encounter and criteria used to identify and classify clicks.
Figure 3. Example of target motion analysis feature of PAMGuard’s ViewerMode software.

PAMGuard’s ViewerMode module uses proprietary ‘binary files’ and an Access database produced during processing to replay all of the data collected during a survey. Using ViewerMode, click trains events can be reviewed and marked, as shown in Figure 2 panel (I). Panel (I) shows a time/bearing display with time along the x-axis, and bearing from the ship from 0 to 180 degrees along the y-axis. Individual beaked whale tracks are color coded. Panel (II) shows the click waveform (amplitude [y-axis] versus time [x-axis]), panel (III) shows the click spectrum (amplitude [y-axis] versus frequency [x-axis]) and panel (IV) shows the Wigner-ville transform plot (frequency [y-axis] versus time [x-axis]). These windows are displayed for any echolocation click that has been selected. These click characteristics are important for identifying or confirming the biological source of a click as well as species identity. Panel (V) is an example of a spectrogram (frequency [y-axis] versus time [x-axis]) that is used both in real time and in post-processing to allow the data analysts to confirm species identity.

In this analysis, the average of the left and right slant ranges distances was used for distance sampling analysis.

Information from the waveform (duration: ~0.15–0.5 ms) spectrum (frequency peaks: Baird’s = 16–22 kHz, Cuvier’s = 38–40 kHz, and Stejneger’s = 45–66 kHz) and Wigner plot (verification of upsweep in signal) were used to assign mutually exclusive species classifications to all acoustic
encounters of beaked whales (Baumann-Pickering et al. 2013) (Figure 4). Stejneger’s beaked whale designation was based solely on spatio-temporal patterns of beaked whale echolocation signals as described by Baumann-Pickering et al. (2012a; 2012b; 2013). A subset of encounters was selected to measure click trains using PAMGuard Real-time Odontocete Call Classification Algorithm (ROCCA) click measurement tools.
Figure 4. Examples of click features for three species beaked whales encountered in the GOALS II study area. The left panel (a) depicts the waveform, the middle panel (b) is the frequency spectrum, and the right panel (c) is the Wigner plot of a typical Cuvier’s, Baird’s, and Stejneger’s beaked whale echolocation click.
2.4 Density Estimation

Slant ranges for all beaked whale acoustic encounters, corresponding trackline identification number, and transect line lengths were imported into the distance sampling analysis program *Distance* (6.2 release 1; Thomas et al. 2010). *Distance* was used to estimate the detection function, encounter rate, effective strip width and the density and abundance of Cuvier’s beaked whales in the study area. The effective strip width refers to the range from the trackline whereby the number of animals detected outside that range (but within the truncation distance) is equal to the number of animals missed inside of it (Buckland et al. 2001). The following formula was used for abundance estimation (Buckland et al. 2001):

\[
\hat{N} = \frac{nsA}{2wL\hat{P}_a\hat{s}_0}
\]

\(\hat{N}\) = estimated abundance

The fixed (known) variables in this equation are:
- \(A\) = area of the study area (km\(^2\))
- \(L\) = total length of on-effort trackline surveyed (km)
- \(n\) = number of animals acoustically localized
- \(w\) = effective strip half-width surveyed on each side of the survey trackline

The estimated variables are:
- \(\hat{P}_a\) = the average probability of detecting an animal between 0 and \(w\)

The variables and functions with assumed values are:
- \(s\) = animal group or cluster size (for this study \(s\) is equal to 1 because all localizations were assumed to be for an individual whale)

The variables with empirically estimated values are:
- \(g(0)\) = the probability of detecting an animal at distance = 0 (i.e., on the trackline)

For this study, \(g(0)\) was calculated using equation 1 from Barlow et al. 2013:

\[g(0) = \frac{(E(a) + w)}{(E(a) + E(u))} = 0.51\]

where:
- \(E(a)\) = the time spent actively foraging (0.582 from Barlow et al. 2013 Table 2)
- \(E(u)\) = the total time spent between foraging dives + the time spent in foraging dives but not clicking (1.51; calculated from Tables 1 and 2 in Barlow et al. 2013)
- \(w = 2* k/v\) where \(k\) = the effective strip width (3.56 km) and \(v\) = the average survey speed (14.8 km).

Density was calculated as \(\hat{D} = \hat{N}/A\) (km\(^2\)) where \(\hat{D}\) = estimated density

Prior to analysis, distances beyond 5 km were truncated. Data truncation is a standard distance sampling analysis tool used to improve the fit of the detection function model and reduce
potential bias in the detection probability estimate (Buckland et al., 2001). The remaining range
data were transformed into five bin intervals (0–2 km, 2–3.5 km, 3.5–4.5 km, and 4.5–5 km). This
was done to account for the fact that distances are slant ranges and that the difference between
the slant range and the true perpendicular distance is greatest near the trackline and decreases
thereafter. Therefore, bins decrease in size away from the trackline. Several types of detection
function models were fit to the data to estimate the probability distribution of distances from the
trackline. Detection function models include a key function and adjustment terms can be added
for additional flexibility (Buckland et al 2001). The key functions included both Hazard-Rate and
Half-Normal models with and without adjustment terms using both conventional and multi-
covariate distance sampling methods. Multi-covariate distance sampling allows additional
covariates, which may affect detectability, to be included in the detection function model
(Marques et al., 2007). In this analysis, multi-covariate models included stratum type as a
covariate as a proxy for oceanographic conditions that may have affected sound propagation,
and hence detectability of clicking beaked whales. Akaike’s Information Criterion (Akaike 1973)
was used for selection of the best fit model. For all final models, variance estimates and
confidence intervals were obtained using a nonparametric bootstrap to resample lines (n= 999)
within strata as described in Buckland et al. (2001).
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3. Results

3.1 Towed Hydrophone Array Monitoring and Recording

A total of 23 days of acoustic effort was conducted during the line-transect survey. This resulted in 426 hours of ‘standard’ real-time monitoring for approximately 6,304 km of trackline (Table 2). This represents an average of 18.5 hours and 274 km of acoustic monitoring effort per day. There were 93 acoustic encounters with beaked whales (32 Baird’s, 47 Cuvier’s and 14 Stejneger’s), of which 79 (85 percent) were localized during post-processing (Table 2; Figure 5). Of these localized encounters, a total of 18 Baird’s, 40 Cuvier’s and 10 Stejneger’s occurred during line-transect effort. The Cuvier’s beaked whale was the only species of beaked whale with a sufficient sample size for density and abundance estimation.

Table 2. Number of beaked whale encounters by species. The total number of encounters, the number of encounters localized during post-processing and the number of localized encounters that occurred during line-transect effort.

<table>
<thead>
<tr>
<th>Species</th>
<th>Encounters</th>
<th>Localized Encounters</th>
<th>Localized Encounters During Line-Transect Effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stejneger's beaked whale</td>
<td>14</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Baird's beaked whale</td>
<td>32</td>
<td>29</td>
<td>18</td>
</tr>
<tr>
<td>Cuvier's beaked whale</td>
<td>47</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>93</strong></td>
<td><strong>79</strong></td>
<td><strong>68</strong></td>
</tr>
</tbody>
</table>
Figure 5. Map of all beaked whale acoustic encounters.

A subset of encounters with individual beaked whales was used to measure echolocation click parameters for each species (Table 3; Figure 6).
Table 3. Echolocation click measures by species. Each parameter is listed with corresponding values for the median, 10th and 90th percentile.

<table>
<thead>
<tr>
<th>Species</th>
<th>Cuvier’s Beaked Whale</th>
<th>Species</th>
<th>Baird’s Beaked Whale</th>
<th>Species</th>
<th>Stejneger’s Beaked Whale</th>
</tr>
</thead>
<tbody>
<tr>
<td># of clicks</td>
<td>199</td>
<td># of clicks</td>
<td>1109</td>
<td># of clicks</td>
<td>62</td>
</tr>
<tr>
<td># of Individuals</td>
<td>10</td>
<td># of Individuals</td>
<td>26</td>
<td># of Individuals</td>
<td>5</td>
</tr>
<tr>
<td>Parameter</td>
<td>Median</td>
<td>10th Percentile</td>
<td>90th Percentile</td>
<td>Parameter</td>
<td>Median</td>
</tr>
<tr>
<td>Peak Frequency (kHz)</td>
<td>39.38</td>
<td>35.44</td>
<td>42.68</td>
<td>Peak Frequency (kHz)</td>
<td>16.88</td>
</tr>
<tr>
<td>Duration (µs)</td>
<td>151.04</td>
<td>109.152</td>
<td>182.29</td>
<td>Duration (µs)</td>
<td>83.30</td>
</tr>
<tr>
<td>Center Frequency (kHz)</td>
<td>38.23</td>
<td>36.08</td>
<td>39.67</td>
<td>Center Frequency (kHz)</td>
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<td>7</td>
<td>13</td>
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*Outliers removed prior to analysis.
Figure 6. Boxplots of echolocation click measures by species (Bairds = Bb = Blue; Stejneger's = Ms = Green; Cuvier's = Zc = Orange).
3.2 Cuvier’s Beaked Whale Abundance/Density Estimates

A total of 40 on effort localized Cuvier’s beaked whale encounters were used to estimate density and abundance. The number of encounters varied by strata, with 8 encounters occurring in the offshore stratum, 26 encounters in the seamount stratum and 6 encounters occurring within the slope stratum (Figure 7). The slant range distances of the localizations were initially reviewed to assess the distribution of observed slant ranges and determine appropriate bin intervals prior to distance analysis (Figure 8).

Figure 7. Towed hydrophone array effort and on line-transect effort Cuvier’s beaked whale localized acoustic encounters along the GOALS II survey tracklines.
There were insufficient data to fit detection function models independently to each of the strata; therefore, the data were pooled across strata, and a global detection function was estimated. A conventional distance sampling Half-Normal model with no adjustment terms or covariates resulted in the lowest Akaike’s Information Criterion value. Consequently, this model was selected as the best fit model and used to estimate abundance and density. Based on this detection function (Figure 9), the estimated effective strip half-width was 3.56 km and the probability of detection was 0.71.
Figure 9. Global detection function for the Half-normal model showing detection probability (y-axis) vs. slant range distance in kilometers (x-axis).

Encounter rates (animals/km surveyed) were estimated separately for each stratum (Table 4). Encounter rate varied by strata and was highest in the seamount stratum (10 animals/1,000 km), followed by the offshore (7 animals/1,000 km) and slope strata (3 animals/1,000 km), respectively. These encounter rates and the global detection function were used to estimate density and abundance for each of the three strata. The global density was estimated as the mean of stratum estimates weighted by stratum area. An acoustic-based density and abundance estimate was obtained for each estimate was obtained for each stratum where Cuvier’s beaked whale encounters occurred (Offshore: \( \hat{D}/1,000 \text{ km}^2 = 0.20; \hat{N} = 122; \text{CV}_b = 48\% \); Seamount: \( \hat{D}/1,000 \text{ km}^2 = 0.30; \hat{N} = 138; \text{CV}_b = 30\% \); and Slope: \( \hat{D}/1,000 \text{ km}^2 = 0.08; \hat{N} = 31; \text{CV}_b = 74\% \)) and for the entire survey area (\( A = 142,204 \text{ km}^2; \hat{D}/1,000 \text{ km}^2 = 0.21; \hat{N} = 291; \text{CV}_b = 28\% \)) (Table 4).

Table 4. Distance sampling results for best fit model. Variance and confidence intervals were obtained using nonparametric bootstrap to resample lines (\( n = 999 \)) within strata (denoted by subscript b).

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<td>(0.17–0.56)</td>
<td>(0.02–0.36)</td>
<td>(0.12–0.36)</td>
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<tr>
<td>Abundance</td>
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<td>251</td>
<td>57</td>
<td>291</td>
</tr>
<tr>
<td>Abundance 95% Cl(_b)</td>
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<td>(77–253)</td>
<td>(8–131)</td>
<td>(165–516)</td>
</tr>
<tr>
<td>CV(_b)</td>
<td>48%</td>
<td>30%</td>
<td>74%</td>
<td>28%</td>
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The overall pooled abundance estimate for the entire study area was 291 animals. This equates to 0.21 animals per 1,000 km² for the study area, which includes three of the four surveyed strata (slope, offshore and seamount regions; 142,204 km²). This should be considered the minimum density of Cuvier’s beaked whales in the study area given the assumptions and biases described below. Cuvier’s beaked whale density estimates were highest for the seamount stratum (0.30/1,000 km²) compared to the offshore and slope strata (0.20 and 0.08/1,000 km², respectively). This suggests that Cuvier’s beaked whales in the GoA exhibit a habitat preference for the seamount region. As such, predictive habitat modeling analysis may be of significant value for management planning.

There are two main caveats to consider for this analysis: (1) slant ranges were measured rather than standardly used perpendicular distances, and (2) g(0) ≠ 1 (i.e., not all animals on the trackline are available for detection). In this study, the first caveat was treated as a measurement error issue. Measurement error can be especially problematic with deep-diving whales that occur near the trackline. This type of error is due to the measurement of slant ranges rather than horizontal distance from the trackline. In this situation, measured perpendicular distances would be overestimated, resulting in a wider effective strip width and, therefore, an underestimation of the true density and abundance. To handle this potential bias, the data were grouped into larger bin intervals prior to analysis. Grouping (i.e. binning) data can be used in some circumstances to improve the fitting of the detection function model and can lead to more robust results (Buckland et al., 2001). However, this approach relies on the data to be grouped correctly. In this study, bin sizes were selected based on knowledge of the animals’ diving behavior; however, it is not possible to be certain that the measurement error caused by using slant ranges has been completely eliminated using this method. An examination of underestimation bias using the offshore and seamount data from this study was undertaken to compare a conventional model with and without the binning method applied to a method that incorporated depth distribution into the detection function to account for the slant range bias (Yack et al. 2015). This study demonstrated that using a binning method reduces underestimation bias by a factor of five (i.e., from 20 percent to 4 percent) (Yack et al. 2015).

The second caveat is that the g(0) value used (0.51) was calculated based on data collected using D-tags, TDR and Satellite tags. However, the tag data used to assess the time spent foraging and diving were obtained from animals tagged in other locations (Ligurian Sea, Hawaii, Southern California). For Cuvier’s beaked whales, the fraction of time spent in foraging dives was significantly related to tag type/location, but the proportion of time spent actively foraging during a foraging dive was not (Barlow et al. 2013). As such, dive behaviors of Cuvier’s beaked whales in the GoA may vary with respect to relative time spent engaged in foraging activity. A tagging study on beaked whales in the GoA during the same period as the survey would be needed in order to obtain a more accurate estimate of g(0). However, the g(0) estimate used herein provides a better approach to estimating Cuvier’s density and abundance than just assuming that g(0) = 1.
Given these caveats, if the estimates reported herein are biased they would most likely be biased downward (i.e., if binning does not fully correct the slant range bias or if there is bias in the g(0) estimate).

This study demonstrates that density and abundance for beaked whales can be estimated using acoustic data from line-transect surveys. These methods can also be used to estimate beaked whale density and abundance in other regions. Results from this study represent the first density and abundance estimates for Cuvier’s beaked whales in the central GoA and, more importantly, the first acoustic-based estimates from a line-transect survey for any species of beaked whale. Although visual detections of Cuvier’s beaked whales (and other beaked whale species) were made during this survey, the resulting sample size was insufficient to obtain a visual-based estimate of density and abundance for this species. Given the cryptic surfacing behavior of beaked whales, and the persistent inclement weather and sea conditions that occur in the GoA, alternative methods of determining species occurrence and distribution are essential if density and abundance of these species are to be estimated reliably. In this study, acoustic data were analyzed using traditional distance sampling methodology. This approach is robust and can be easily adapted for acoustic data to estimate density and abundance of other deep-diving and/or elusive odontocetes. Although there was not a sufficient number of Baird’s beaked whale or Stejneger’s beaked whale acoustic encounters from this survey to reliably estimate density and abundance of these species, another survey in the GoA study area would likely provide the additional samples needed to do so. The information provided on Cuvier’s beaked whale density, abundance, and distribution is critical for conservation and management of this federally protected species. These results can be used to support future environmental management and planning by the Navy and other agencies.
5. Acknowledgements

We would like to acknowledge Robin Brake and the Deputy Assistant Secretary of the Navy for the Environment’s office, as well as Commander, Naval Operations N45. We would also like to thank Naval Facilities Engineering Command (especially Joel Bell and Sean Hanser) for supporting the analysis effort, and HDR, Inc., especially Kristen Ampela for support and coordination of all project logistics. We would also like to thank Danielle Harris and Len Thomas from the Centre for Research into Ecological and Environmental Modelling at the University of St. Andrews for their advisory role in the distance sampling analysis. We also thank Douglas Gillespie for PAMGuard software support, Jay Barlow for advice on g(0) estimation, and Elizabeth Becker for reviewing this report. A special thank you for the tireless and dedicated efforts of the survey acousticians: Jessica Crance and Dawn Grebner, as well as to John Calambokidis and Cascadia Research Collective for survey planning, coordination, and support. We would also like to thank all of the participants of the survey: Jeff Foster, Annie Douglas, Michael Richlen, Jennifer Gatzke, Ernesto Vasquez and Bridget Watts, as well as the captains and crew of the R/V Aquila.
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6. References


Cuvier’s Beaked Whale Encounters Used in Distance Analysis
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